A LABORATORY STUDY ON ANNOYANCE DUE TO WIND TURBINE NOISE

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ABSTRACT

In the energy industry, renewable energy has been encouraged to substitute fossil fuels. Accordingly, wind market keeps growing, but noise from wind turbines cause annoyance to residents living in the vicinity of wind turbines and lead to environmental noise problems. In Europe, several studies on the adverse effects including annoyance from wind turbine noise have been conducted and the results have been compared to the annoyance from transportation noise. Furthermore, European countries established the environmental noise regulations of wind turbine noise. The Wind turbine noise has amplitude modulation which causes the swishing sound in audible frequency bands so that it is easy to perceive the noise. In addition, the amplitude modulation is varied with the azimuth angle around wind turbine, so annoyance from wind turbine noise may differ according as listener′s locations. Therefore, in the present study, all stimuli are generated using numerical schemes along with azimuth angle and distance, and added the ambient noise to simulate real environment. Then, the subjects assessed noise-induced annoyance to randomly played sounds based on 7 point numerical scale. The result showed that wind turbine noise causes the most highly annoyance at an azimuth angle of 60 degrees. Moreover, relationships using several sound descriptors and subjective annoyance were examined. As a result, an index which provides better explanations of distinguishing annoyance characteristics to wind turbine noise was proposed.

1. INTRODUCTION

The world today is paying attention to renewable energy. Wind power is one of the most promising sources, and due to its possibility for indefinite production of energy, the industry has grown steadily over recent years. However, the noise induced by the wind turbine has been an obstacle for ongoing growth.

According to recent studies, the noise from the turbine could have an adverse effect on health and especially in the night it could cause sleep disturbance [1]. Moreover, the percentage of people who were annoyed by wind turbine noise at low exposure levels was higher than the percentage of people who were annoyed by transportation and other industrial noise at much higher levels. Certainly, transportation and industrial noises are louder than wind turbine noise. But owing to its specific characteristics, the residents have complained of displeasure on the wind turbine noise [2].

The noise from wind turbine could be categorized as mechanical noise and aerodynamic noise which accounts for a bigger portion. The aerodynamic noise is generated by fluid-structure interactions on the blades which causes several sources of noise, among which the trailing-edge noise is the most continuous and strongest source. The trailing-edge noise causes amplitude modulation due to atmospheric effects and directional propagation effects, which causes the whooshing or beating sound [1].

Several studies indicated that the noises having amplitude modulation are easier to be perceived than constant noises even at far distance and have been found to be more annoying.[3][4] Additionally, as the wind turbine noise is highly susceptible to wind velocity and wind is not consistent, the noise is unpredictable and difficult to control. As a result, the wind turbine noise is more irritating compared to other noises [5][6].

There have been many researches analyzing the characteristics of the sound from wind turbine and also studies on the adverse effects of the noise on human. However there have been only few studies regarding the relationship between annoyance and sound metrics, and therefore more researches associating noise-induced annoyance relates to attributes of wind turbine noise are needed [2].

In this study, to assess the degree of annoyance of subjects, all stimuli were simulated by numerical methods and a psycho-acoustic test for noise-induced annoyance was conducted. And regression analysis was performed to generalize the indicator that could explain the result of experiment. From the analysis, the angle at which annoyance response due to wind turbine noise were biggest was confirmed and the sound descriptor which correlates with most strongly annoyance current was suggested.

2. METHOD

2.1 Stimuli

Stimuli for this study were generated using numerical schemes based on 2.5MW wind turbine and other conditions and validation can be confirmed at previous study [7]. Considering the sound absorption by atmospheric effect, humidity condition was set to 60% and the sound level was attenuated at each frequency. Selection criteria of the number of stimuli were based on the distance and azimuth angle around the wind turbine. The azimuth angles had 7 types spaced at 15° apart (0°, 15°, 30°, 45°, 60°, 75°, 90°) and distances had 4 types from 128m to 1000m (128m, 250m, 500m, 1000m).

When the azimuth angle around the wind turbine was divided into 4 quadrant, the distribution of noise level at each quadrant is nearly similar. So, overall distribution of annoyance could be judged via below quadrant [8].

According to the previous studies, when the residents dwelling around the wind turbine were exposed to the wind turbine noise, 85% of them could recognize even about 35 dB(A) [9]. Since the sound level at 1,000 m was about 35 dB(A), the distance for stimuli was limited to 1,000 m. Background noise level was set to 40 dB and playback time of stimuli were designed as 15s.

2.2 Hearing experiment

Thirty two test subjects participated in the test(male : 17, female : 15) and they were 20 to 33 years old, with an average of 25.7 years. All subjects underwent audiometry-screening test that progressed as pure tones which were 15~20 dB over than RETSPL(Reference Equivalent Threshold Sound Pressure Level) at central frequency in octave band (125Hz~8kHz). Then, they were considered to have normal hearing when they perceived those signals [10] . In the questionnaire, annoyance from wind turbine noise was assessed with a 7-point numerical scale: “highly annoyed” = 7, “do not notice” = 1.

The listening tests were conducted in an anechoic room and the stimuli were presented by headphones. The sound pressure levels of the stimuli were calibrated everyday by checking the output signal of HATS. On completion of the hearing tests, subjects described the component of noise that caused the most annoyance.

3. RESULT AND DISCUSSION

3.1 Annoyance response to wind turbine noise

Annoyance response from the experiment differed depending on azimuth angles and distances as shown in Fig. 2(a). Interestingly, annoyance due to wind turbine noise depends on listener’s location even at the same distance from wind turbine. Annoyance tends to increase from 0° to 60° and has the biggest value at 60° of all distances. After 60°, an annoyance decreases rapidly.

OASPL(overall sound pressure level) at each point was calculated to inquire magnitude of sound. The equivalent level is the most-used measure for showing the physical strength of the sound. When compared between azimuth angles, generally the overall sound pressure level becomes lower as the angle gets closer to 90° due to directivity pattern of sound emitted from blade. (Fig. 2 (b)).

Since the experiment was subjective evaluation for wind turbine noise, to find out whether there were any significant differences between 60° and other angles, within-subject design analysis was conducted. As a result, the p-values were less than 0.05 indicating a confidence level higher than 95% at all pairs. Therefore, it was concluded that there was a statistically significant difference between 60° and other angles and the angle at which the noise was most annoying was 60°.

Additionally, it could be said that the index considering only physical property was not enough to make an explanation for the result.

3.2 Comparison of annoyance response with sound descriptors

Generally, annoyance is derived from the emission level of the sound. So, in European countries, there were many researches on relation between degree of annoyance and noise level. [6] According to their studies, though the regulations for wind turbine noise are different in countries, most of the guidelines commonly regulated sound pressure level for the noise using equivalent measure about 40~50 dB, which is more strict than other noise criteria. But they have no regard for the change of acoustical characteristic with location.

At the first step of analysis, L_{Aeq} which regards the response of the human ear was used to calculate the magnitude. As referred to earlier, there were many researches to figure out the relation between annoyance and wind turbine noise level of L_{Aeq}.

To understand directly the correlation between annoyance and the indices above, R-squared value was calculated by regression analysis in Fig 3(b). The inclination of change of those measures is positive and the R-square value is quite high and the correlation of annoyance is explained well. But in detail at the same distance, as the L_{Aeq} increases the degree of annoyance becomes lower. Wind turbine noise varies with time periodically, it has level difference between the maximum and minimum level. Thus, the subjects perceive dominantly the maximum level of the repeated noise and show their displeasure. But, the L_{Aeq} is the measure which take the minimum level of the noise into account and gets average over the whole period so that leverage of the maximum level is not sufficiently reflected.

The following procedure is examined with loudness which is an psychological indicator used to consider physical strength and human auditory sensation [4]. Loudness is not an objective measure but a subjective measure so that it is used widely for assessment of annoyance. Since the psycho-acoustic experiment was also judged participants' subjective evaluation, loudness could be relevant to correlation analysis. The loudness of stimuli compared with azimuth angle is plotted in Fig. 4 (a). The level decreased significantly compared to the results of L_{Aeq}.

At first, Loudness is calculated by integration of specific loudness. The specific loudness depends on frequency band. The nearer the crosswind direction, the stimuli showed great reduction in energy at low frequency. Moreover, since there is little difference of the amount of energy on high frequency among stimuli. So, as the azimuth angle gets wider on the contrary, the loudness decreases significantly.

In regression analysis (Fig. 4 (b)), R-squared value is less than that of energy equivalent indices. And as the loudness increases the level of annoyance becomes lower at the same distance in detail. Loudness usually means stationary loudness. Stationary loudness is compatible with sound which has little variation of level. For that reason, the feature of wind turbine noise which has amplitude modulation could not be described by loudness.

For different means, fluctuation strength was used to inquire the correlation with annoyance. The relatively unique characteristic of the wind turbine noise is amplitude modulation. That means the sound level of signal varies periodically at time. Besides, amplitude modulation is known to be a factor that makes the noise easy to be perceived and so it could have a significant effect on the degree of annoyance.

The values of fluctuation strength with azimuth angle in Fig. 5 (a) show the similar trend with the values of annoyance response with azimuth angle in Fig. 2 (a). And in Fig. 5 (b), the fluctuation strength correlates well with annoyance compared to the former descriptors with a higher R-squared value. But at the same distance in Fig.5 (a), the fluctuation strength has not the biggest level at 60° of azimuth angle. The reason why fluctuation strength cannot fully explain the annoyance results can be explained by two reasons: modulation frequency of the wind turbine noise is too low, and fluctuation strength is calculated with time variation of specific loudness. Firstly, fluctuation strength has great significance relatively when the modulation frequency is about 4 Hz. But since there is a limit in raising RPM in most of the wind turbines, modulation occurs only at about 1 Hz, so effect of fluctuation strength itself on annoyance is not strong enough. In addition, because masking effect is hardly considered for low modulation frequency and masking depth was hard to be defined as single value, it is substituted for the corresponding difference in specific loudness.

As the distance is far from wind turbine, the energy at higher frequency is reduced more rapidly than at lower frequency. In effect, distribution of energy on frequency domain has different patterns even at same angle. Thus, the trend of difference of specific loudness calculated with sound energy severely varies with the distance and the variation of fluctuation strength with azimuth angle does not show consistency as the distance increases.

The last step of analysis was performed with the maximum A-weighted level (L_{Amax}). Descriptors by energy-averaged(equivalent) calculation and the characteristics concerning the modulation depth were applied to analyze the trend of annoyance for wind turbine noise. As stated above, because the wind turbine noise has a low modulation frequency, the masking effect does not need to be regarded. Thus, the difference of the noise level between the maximum and minimum is clearly perceived and an annoyance could be mainly caused from the maximum level. Therefore, the noise was evaluated with the L_{Amax} and the correlation of the L_{Amax} and annoyance was analyzed. The result is as following Fig. 6. L_{Amax} was the biggest at 60° of azimuth angle and the trend of

L_{Amax} was similar with Fig. 2 (a). Also, R-squared value of the L_{Amax} was significantly higher than the other measures. Therefore, it is concluded that L_{Amax} was the most appropriate index for explaining the annoyance due to wind turbine noise which cause amplitude modulation repeatedly.

4. CONCLUSION

In the present study, a psycho-acoustic test was implemented using wind turbine noise. From this experiment, the annoyance response with azimuth angle due to wind turbine noise was obtained and analysis regarding acoustical characteristic was performed to find out the index which best fits to the annoyance response.

Since the noise varies periodically with time and this causes amplitude modulation, the energy equivalent indices cannot reflect precisely the annoyance of subjects considerably affected by the maximum level. In addition, the masking pattern was less effective by low modulation frequency. Therefore, the difference of the maximum and minimum level could be apparent and the noise which has the bigger maximum level causes annoyance more.

As a result, it was statistically confirmed that the annoyance from wind turbine noise on downwind direction is the biggest at 60° of azimuth angle and L_{Amax} of sound can comparatively well explain annoyance response among above descriptors. This means the annoyance response due to wind turbine noise should be assessed in terms of listener’s location. And this study can be used for planning an installation of wind turbine considering the relationship of noise-induced annoyance and residents as a reference.

5. ACKNOWLEDGEMENT

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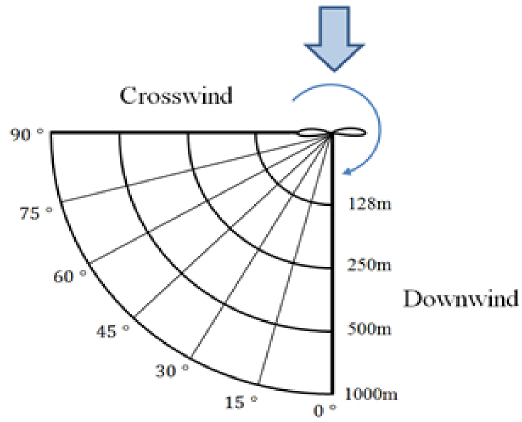

Fig. 1 Distances and azimuth angles for stimuli

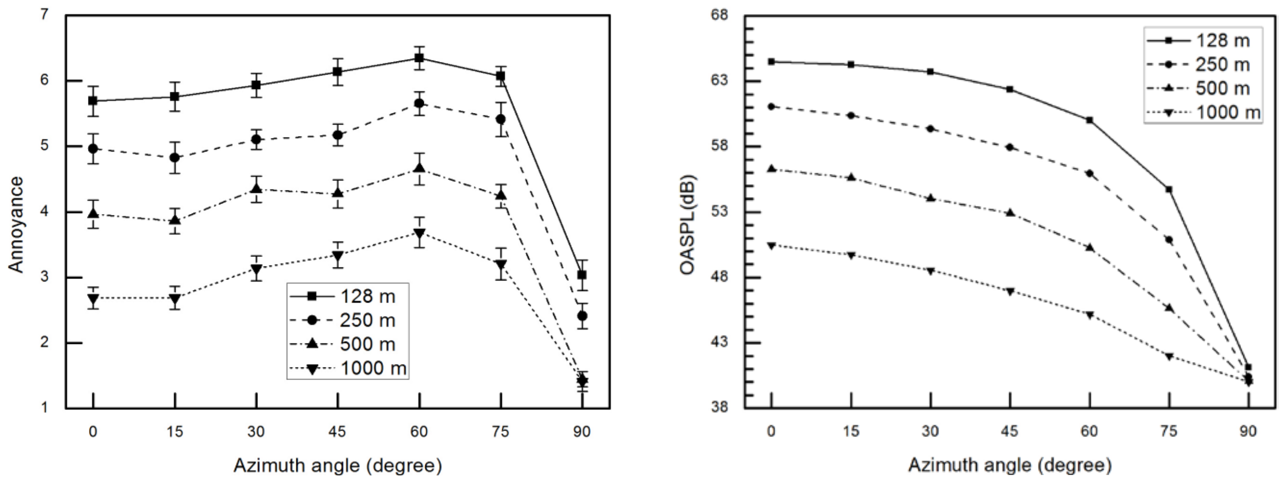

Fig. 2 (a) Annoyance response with azimuth angle (b) Leq with azimuth angle

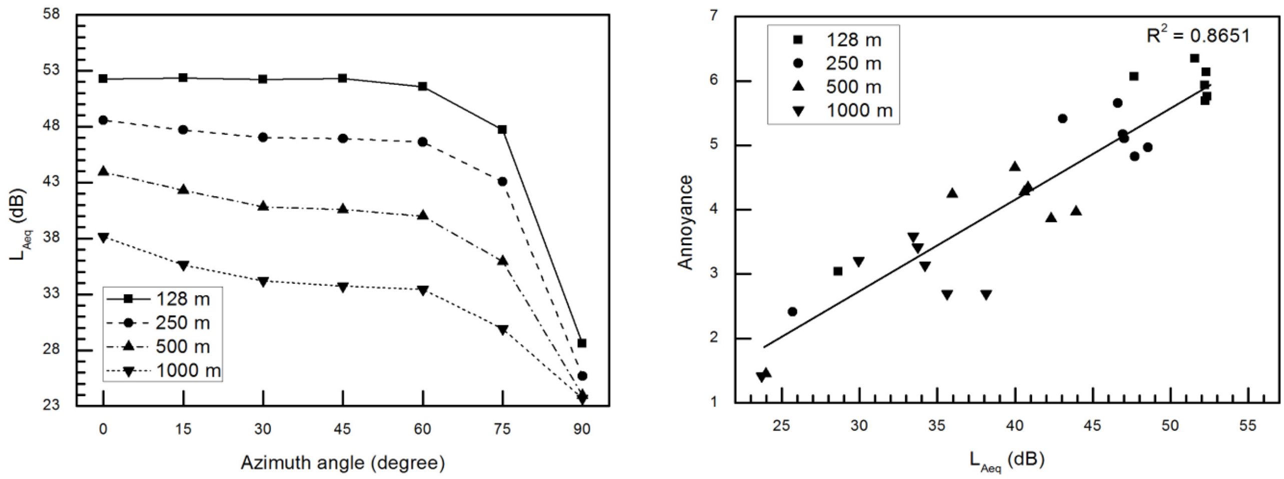

Fig. 3 (a) LAeq with azimuth angle (b) correlation between annoyance and LAeq

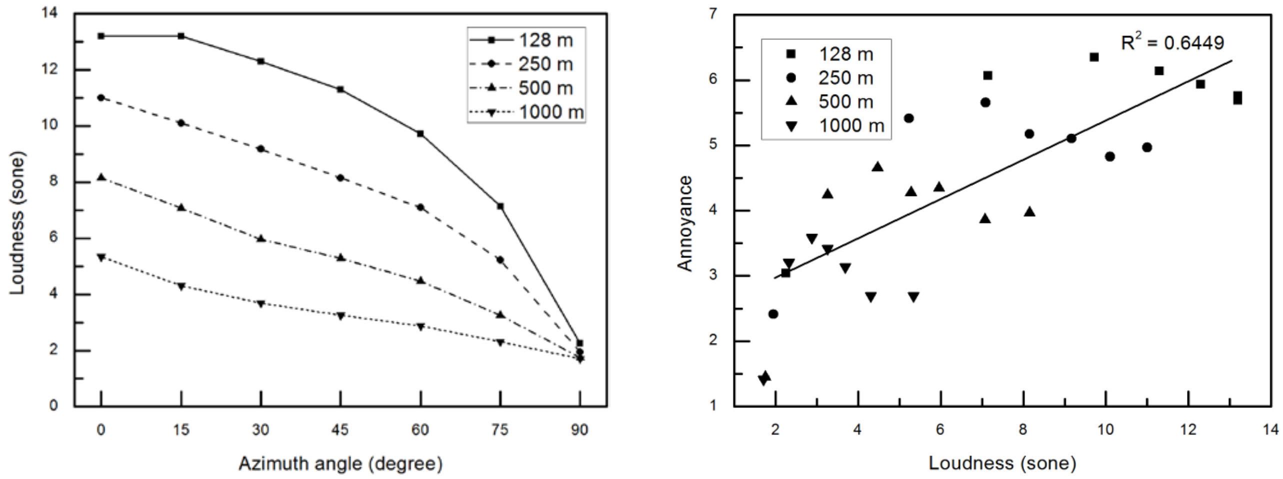

Fig. 4 (a) Loudness with azimuth angle (b) correlation between annoyance and loudness

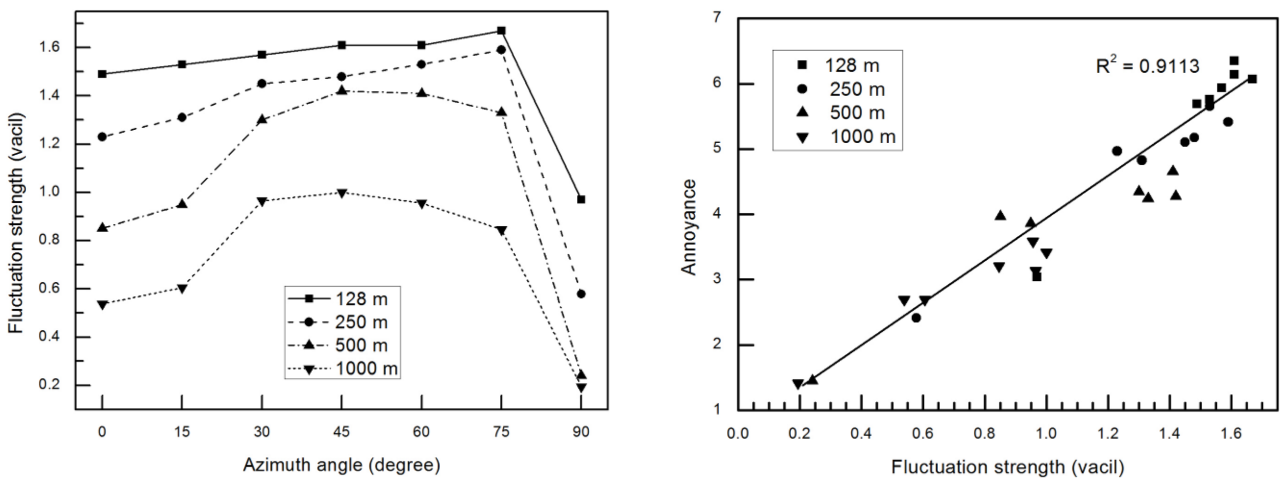

Fig. 5 (a) Fluctuation strength with azimuth angle (b) correlation between annoyance and fluctuation strength

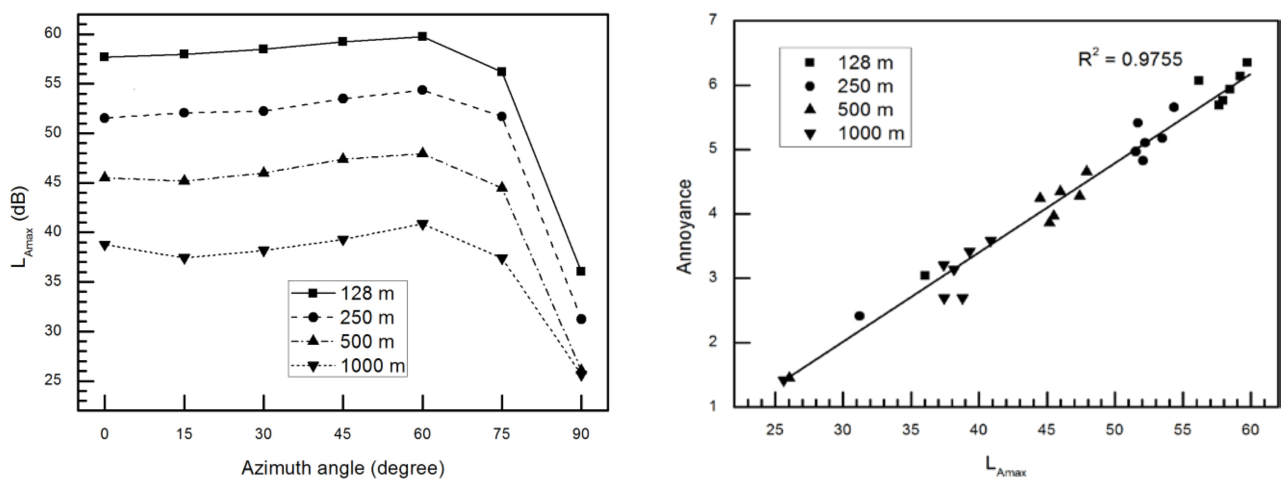

Fig. 6 (a) L_{Amax} with azimuth angle (b) correlation between annoyance and L_{Amax}